

A Sustainable Human Economy

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Any human economy can be characterized and measured in terms of its energy use. And the internal workings of any human economy may be described by the equality or inequality of energy ownership or benefit among the population. All energy sources on the earth with the exception of nuclear depend on the input of solar energy. Wind energy, wave energy, biomass energy, and all fossil fuel energy (coal, oil, and natural gas) involve immediate or stored energy from the sun.

Human economic growth comes at the expense of appropriation of land, sunlight, natural resources and other life forms. The earliest human economies involved hunting and gathering by very small numbers of humans in relation to the ecology in which they lived. Outside of humans, this is similar to every other form of life in the ecology. This economy was ecologically sustainable as long as the ecology was not overwhelmed by natural processes such the massive climate change in the form of droughts, volcanic activity, ice ages and other large-impact events. Early humanoids and then humans like ourselves fit comfortably into the existing ecology and simply added another sustainable species to the rich mix of life forms on the earth.

Humans began to move toward unsustainable impacts, however, over the last 5,000 to 10,000 years as the human economy moved away from hunter/gatherer mode to agricultural and animal domestication mode, then to advanced agricultural mode, then to coal-powered industrial mode, and finally to oil and natural gas-powered technological mode. The industrial revolution brought with it a concomitant rapid growth and then explosion in the human population. The change in economic modes were not, by themselves, threatening to the earth ecology but the addition of large numbers of human beings on the planet made possible only by the industrial and technological economic modes has produced great disturbances to the ecology on which all life depends. If the 300,000,000 human beings who lived in the advanced agricultural mode had stayed constant, then a sustainable higher standard of living for all would have been numerically possible in the industrial and technological modes of the economy. We will discuss why the current population of 7.8 billion (10^9) human beings is not sustainable under any of the economic modes humanity has developed. This population is 26 times larger than that of the advanced agricultural mode. Of course, this population has a mix of proportions living in each economic mode even today. The mathematics of the situation will not allow everyone living today to participate equally in the

most advanced technological and economic modes and lifestyles due to ecological limitations.

First let's review the energy use under the respective human economic modes. Proto-humans used about 2,000 kilocalories a day to survive, supplying just the basic needs of the human body. Hunter/gatherers use about 5,000 kilocalories each day by appropriating the energy of plants and animals as food and wood fires used for cooking. Early agriculturalists use about 12,000 kilocalories each day by farming and appropriating agricultural plant and animal products. Advanced agriculturalists use about 26,000 kilocalories each day using more organized agriculture involving monoculture, irrigation, fertilization, crop rotation, use of animal energy and advances in farm technology. Industrial society uses about 77,000 kilocalories each day making use of wind and fossil coal as fuels and associated technologies, inexpensive global trade and rapidly shifting financial and legal structures. Technological society uses about 230,000 kilocalories for each person each day by adding fossil oil and natural gas, the generation, transmission and battery storage of electricity, nuclear energy technology and ever advancing electronic, mechanical, control and biological science technology.¹

¹ See I.G. Simmons, Changing the Face of the Earth: Culture, Environment, History, Second Edition (Cambridge, Massachusetts: Blackwell Publishers, Inc., 1996), p. 27, where Simmons categorizes human economic systems and

These developments in economic organization beyond the hunter/gatherer mode don't necessarily pose a threat to the earth ecosystem and the human future. But the current human population and the more than exponential growth of the human population over the last 600 years does pose such a risk.² A human population of 300,000,000 (Cohen's high range estimate for the year 1 of the Common Era) with current technologies is a very different thing than our present population of 7,800,000,000. The current population is 26 times larger than that of 1 CE. If we had a population of 300 million today we could use 96% less in finite resources each year to maintain our current average standard of living.³ This would mean 96% less pollution and 96% less devastation of soil, water and air resources. And this means 96% less human burden upon the earth ecosystem. The current 600 Quads (600×10^{15} Btu) of energy that we use globally each year could be

specifies the daily per capita energy consumption of each system in terms of kilocalories, what we normally refer to as Calories when we consume food. Proto-humans consumed 2,000 Calories per person per day, just enough to keep their bodies going. Hunter-gatherers advanced to using 5,000 Calories per person per day, having mastered the use of fire. Early agriculturalists use 12,000 Calories per person per day, raising crops and using animals for their energy and food value. Advanced agriculturalists moved to 26,000 Calories per person per day, using wind and water energy and more advanced agricultural technologies. Industrial civilization jumped to 77,000 Calories per person per day, with wood and coal and steam engines. And technological civilization leaped to 230,000 Calories per person per day, with advancements in science and techniques of all kinds. These are average values. The benefits of all these Calories of average use per person per day are very inequitably distributed among the populations in each economic mode, so that some benefit far more than others from all this energy use.

² Exponential growth involves a constant growth factor over time. For example, it might involve a 3% per year growth rate and the growth over 100 years then would be 1.03^{100} or more than nineteen times the original amount. Human population growth over the last 100 years has been more than exponential in that the rate of increase has not been constant but has grown over time. See Joel E. Cohen, How Many People Can the Earth Support (New York, New York: W. W Norton, 1995), Chapter 5, "Human Population History in Numbers and Graphs," pp. 76ff.

³ Divide 100% by 26 (7.8 billion/.3 billion=26) which equals 3.8. Subtract 3.8 from 100 which equals 95.7 or about 96%.

reduced by 96% to 24 Quads while maintaining an average annual Btu per person of 77,000,000 or an average daily Btu per person of 210,000. Converting Btu to kilocalories, this equals 53,000 kilocalories per person per day. This energy use is about twice that of advanced agricultural society and 70% of that of industrial society. (One Btu equals .252 kilocalories and one kilocalorie equals 3.97 Btu.)

As we know, economic benefits are distributed very unevenly across the human population. Inequality in the distribution of economic benefits turned sharply upward with the evolution of the agricultural mode of human civilization. And each new mode of economic life—advanced agriculture, industrial, technological—has led to increased inequality in the distribution of benefits. Not since the hunter/gatherer mode of life have economic benefits been distributed at all evenly. Using the Gini index, where 0 equals perfect equality, we can estimate the index value for each economic mode: proto human, 0.00; hunter-gatherer, 0.02; agricultural, 0.30; advanced agriculture, 0.50; industrial, 0.70; technological, 0.80. On a worldwide scale economic growth and technological advancement has not resulted in greater equality. In the twentieth century social scientists often described this situation as one in which social institutions did not advance along with economic institutions and technology. Social and political

institutions did not evolve to represent the broad population, at local or regional, national or international levels.

However, the current uneven distribution of economic benefits is only one issue we need to face. An even more demanding issue is intergenerational equity. What kind of a world and what level of finite resources does one generation leave to the next, and the next, and the next, and so on.⁴ This issue is rarely if ever directly addressed. Past generations used resources with virtually no regard for future generations or even for their own personal future. We the present generation use energy resources and finite resources of all kinds at a rapid and increasing pace, leaving future generations to take care of themselves as best they can. We don't, as a rule, appreciate what a short time these resources will last at current and projected rates of use nor do we stop to consider how future generations will live. This raises the question of the sustainability of our economic mode and our population trajectory.⁵

⁴ I am taking a generation to be the average age of the parents when their children are born. Twenty-five years is used here as an approximation for the modern period of history. See http://www.ehow.com/print/how_6183717_calculate-human-generations.html.

⁵ "Sustainability" is a slippery term. In this paper we explore how it relates to equity for future generations as well as what equity for a defined length of time implies for current use of resources whose finite quantities are reasonably known. We need to recognize that on this earth truly long-range sustainability of human civilization, say for one million years is out of the question. And ultimately, in billions of years, the earth itself will disappear. In ten or twenty thousand years we may see another ice age that would destroy our present civilization. In the shorter term, global warming may dominate, bringing drastic disruption to human civilization and all of the natural world in the next 100 to 200 years. This puts some bounds on our planning horizon. But collectively we would be wise to establish a global sustainability plan well beyond the one to five years that currently underpin most government and business plans.

Many people are asking how sustainable is our consumption of both renewable and nonrenewable resources. How much of each resource have we used up and how quickly will we exhaust each resource at current or projected consumption rates. And the question I ask is: what time limit does this put on the future of human civilization? We need a quantitative way to address this question.

If impoverishment of any resource is defined as a decline to, say, 1% of the present amount of the resource on the earth, we can work out the time remaining until impoverishment for any finite resource. This is the equivalent of \$100,000 current investment declining to \$1,000. Psychologically we would all agree that our financial position has declined enormously; I will call this level of decline impoverishment. For the numerical calculations I want to do, it is necessary to set a finite floor such as 1%; otherwise, the calculations would involve infinite answers and the calculations will fail.⁶

⁶ At a given discount rate it takes so many years for an initial resource or population to reach one percent of its original value. One could choose an end point other than 1% of course, but I will use 1% in this paper. We begin with the future value formula for discounting, $FV = PV (1+r)^{-t}$. We then rearrange the formula so that the unknown value we seek is the time: $t = (\log F - \log P) / -\log (1+r)$, which in this case $= \log 0.01 / -\log (1+r)$. For example, using a discount rate of 5% or 0.05, $t = \log 0.01 / -\log 1.05 = 94$ years. It will take 94 years for the resource or population to reach 1% of the original amount. Alternatively, one can designate the years for a planning horizon and calculate the discount rate required using the formula: $(1+r) = \text{antilog}(\log 0.01 / -t)$. For example, $(1+r) = \text{antilog}(\log 0.01 / -500) = 1.00925\dots$, where r is approximately equal to 0.925%. For $r = 1\%$, $n = 463$ years. For $r = 0.1\%$, $n = 4,607$ years. This last might be a reasonable planning horizon since it roughly corresponds with the historical record of our past civilization and, by the rule of symmetry, perhaps our future civilization horizon should not be less than our past. This implies that as our past horizon grows, so should our future planning horizon. In any case, we will adopt an approximate 5,000 year planning horizon for illustration purposes. We will see that we must reduce our present resource use rates dramatically and we will look at the tradeoff between economic well being and population size to achieve a sustainable balance within the overall ecology of planet earth.

The original quantity of a resource includes the amount used to date plus the amount of remaining unused reserves. This may be called the common heritage of past, present and future humanity. We generally let the past take care of itself since we can't affect it. We live in the present and take our actions in the present. The future is problematical. We do affect the future. We can plan for the future. We can calculate consequences for the future. But we humans evolved as short range creatures. Proto-humans just wanted to live through the day. We have advanced to the point where we may plan ahead a generation or two, i.e. 25 to 50 years. We have not advanced much further than this. This is our present challenge. Population size and growth, energy and other resource use, massive ecological impacts, the recognition of CO₂ growth in the atmosphere and the dangers of resultant global warming are some of the things pushing humanity to think, plan and act for a longer term.

For decisions about actions and projects dealing with resource depletion, climate change, human population levels and other large-scale issues a key question to answer is: How far into the future should we look? What should be our time horizon? At what future date should we say to our progeny: You are on your own! How many future generations should we care about? If each generation is defined as 25 years, when do we drop future generations from our planning horizon?

On the other hand, how far can we sensibly plan ahead? We are currently about 10,000 years into an interglacial warming period on the earth. Under normal circumstances we might have another 10,000 years before we enter a new glacial period. It is unlikely that our current population level or civilization mode can survive the onset of worldwide glaciation. Should these data points set our practical planning horizon at 10,000 years?

There is no consensus on the proper planning horizon for humanity. Nevertheless, it is useful to run some numbers based on specific planning horizons in order to understand the implications for our lives and the lives of our descendents.

First let's set a baseline for our current practice of not planning for the future.⁷ For our example we'll look at the resource that plays a critical role in our technological civilization, oil. British Petroleum's Statistical Review of World Energy of July 2019 gives 1,780 billion barrels of confirmed remaining oil reserves worldwide and a current annual consumption rate of 35 billion barrels. This puts reserves at the

⁷ Economists tend to believe that human beings intrinsically discount the future by about 5% per year for uncertainty. They cite the long-run interest rate for money borrowed as a basis for this view. This implies that a very short time horizon is rational; thus anything over about 100 years in the future has essentially zero value. It is my opinion that financial criteria play a very limited role in actual human planning. Some actual decisions reflect dramatically high discounting, using up resources as quickly as possible, and others reflect dramatically low discounting, seeming to take a very long view. Economists themselves never analyze anything but the simplest projects using financial interest and discount criteria. We all know that the bigger and more far reaching the decision being made by governments and large corporations the less financial criteria play a role. On the other hand, when opposing large scale decisions, economists and others routinely employ financial criteria as a reason not to proceed. But arbitrary discount rates are no substitute for clear time horizon analysis and asking how many generations of our descendents should be taken into account.

start of 2021 at about 1,678 billion barrels. This means that at the current consumption rate of 35 billion barrels per year there are about 48 years of oil left as of January, 2021. So, exhaustion would occur in 2069 at present rate of use. That's less than two generations away. This kind of calculation should scare us. Barring some catastrophe, most humans on the planet will still be alive in 2069 and will have to face this situation.

But we must realize that the world demand for oil is not constant at 35 billion barrels per year. Instead, growing human populations and economies around the world are driving an annual growth in demand for oil of about 3%. This throws a spanner into our previous calculation of the years left before exhaustion of the known oil reserves. We need to re-calculate, incorporating 3% annual demand growth. Thus,

$$(1/.03)\ln[0.03(1678/35)+1] = 30 \text{ years}$$

Instead of 48 years to exhaustion, we have only 30 years until known oil reserves will be exhausted, if we continue on our current course. This would be in the year 2051, only about one generation from now. Few people appreciate how short is the time horizon of our oil-fueled civilization.

Naturally there is dispute over the quantity of recoverable oil reserves. I have used known reserves of 1,678 billion barrels in my calculations to this point. Few knowledgeable analysts

would suggest that recoverable reserves are larger than twice this number. What would doubling the reserve estimate do for us?

$$(1/.03)\ln[0.03(3356/35)+1] = 45 \text{ years}$$

This optimistic assessment would push the time to exhaustion to 45 years or 2066, just beyond the middle of this century.

This suggests that business-as-usual is not a good option for our civilization's use of oil if we care anything about the lives even of our children, let alone later generations.

Let's now examine the implications of a 5,000 year planning horizon. In other words, at the end of 5,000 years 1% of the present reserves of a resource will still remain. I'm using the formula 100×1.001^{-5000} .⁸ The 0.1% discount rate required for our 5000-year planning horizon is a far cry from economists' usual 5% discount rate. We will look at the implications of this time horizon from two perspectives. The first perspective takes the current population as a given and determines the sustainable and equitable annual use rate of the resource over the 5,000 year time horizon. The second perspective looks at the current average per person use of the resource, takes the sustainable and equitable annual use

⁸ To obtain an exact discount rate that will, after 5000 years, result in 1% of a resource remaining I use the formula $r = 1 - [\text{antilog}(\log 0.01/-t)]$. For example, $r = 1 - [\text{antilog}(\log 0.01/-5000)] = 0.000921\dots$, with $r = .0921\%$ or just under 0.1%. And $t = \log 0.01/-\log 1.000921 = 5000$ years

amount, and asks what population level is needed to maintain the current average per person use rate.

We will continue using oil to illustrate the implications of a longer-term time horizon for resource use and alternatively for population planning purposes. With 1,678 billion barrels of oil remaining, $1,678 \text{ billion} / 5,000 \text{ years}$ equals 336 million barrels of oil per year or 9.19 million barrels of oil per day of equitable use. Compared to our current use of 96 million barrels per day this is a 99% reduction in use. This is a measure of how far out of alignment we are with an equitable sharing of resources with our descendents. Even adopting a human horizon of only 100 years (just four generations) would reduce our equitable use from our current 96 million barrels a day to 46 million barrels a day, a 52% reduction from current use. There is no escaping the dilemma we face. If we adopted a lifetime rather than a generation as our measure, we might take 70 years as a lifetime. Using just one lifetime as our planning horizon results in $1,678 \text{ billion} / 70$ equals 24 billion barrels of use per year and 66 million barrels of use per day. This still represents a 31% reduction from current use to reach an equitable use figure. So we are currently not even looking after the interests of a recently born child, let alone children to be born 5 or 10 or 20 years from now or beyond.

Now let's look at this the other way round. Our current world use of oil is 96 million barrels per day. With a population of 7.8 billion this equals 0.0123 barrels of oil per day for each human being on the earth. One barrel equals 42 gallons so 0.0123 barrels equals about 0.5 gallons per person per day. If we want to adopt a 5,000 year planning horizon and maintain the current per person use of oil what should our population be? We know that the equitable use rate over 5,000 years is 0.92 million barrels of oil per day, or 39 million gallons per day. By division ($0.92/0.123$) we find that we would need a population of 75,000,000 to maintain our current per person per day use of oil (0.5 gallons) across the world. A population of 300,000,000 (equal to that of year 1 of the Common Era) would depress the average use per person per day to about 0.125 or 1/8 gallon.

Using a 100 year time horizon and 46 million barrels equitable use per day (equal to 1.932 billion gallons at 42 gallons per barrel) along with a goal of 0.5 gallons per person, we obtain a population of 3.74 billion people, a 52% reduction from our current population. In other words, one can reduce the use rate by 52% or the population by 52%. Or one could have some combination of reduction in both the use rate and the population in order to maintain a constant per person use of oil over the 100 year time horizon. Longer time horizons

require correspondingly larger reductions in oil use or population numbers or some combination of both.

With a 5,000 year time horizon the only resource, out of 20 major natural resources used in human industry, that allows for a population of 7.8 billion people without a reduction in use in the current use rate is potash. We can't build a civilization on potash. This list of resources includes petroleum, coal, natural gas, bauxite, chromium, cobalt, copper, gold, gypsum, iron ore, lead, manganese, nickel, phosphate, titanium group metals, potash, silver, sulfur, tin and zinc.⁹

There have never been more scientists and engineers of all kinds than there are today. Yet no one has any realistic idea of finding any new source of energy to serve human needs. Scientists believe we have discovered all the sources of energy that exist in the universe. The major remaining mysteries involve dark matter, dark energy and quantum gravity and no one has any idea how we might harness these things to produce energy for use by humankind.

The human species is about 125,000 years old. Industrial civilization is only about 250 years old. Many of the seven billion people alive today take industrial/technological civilization as the norm. With our lifespan at an approximate

⁹ Geology and the Environment, Third Edition, by Bernard W. Pipkin and D. D. Trent (Pacific Grove, CA: Brooks/Cole, 2001), p. 423.

limit of 100 years, no one living in the U. S. or Western Europe can remember any other norm.

All species of life have a short-term outlook. Each member of each species is trying to get through each day with enough food and water, avoid predators and reproduce. We humans aren't fundamentally different. However, because of our unique mental abilities we are able to have enormous impacts on the world and other species. We also have the ability, potentially, to moderate our impacts on the world and achieve a sustainable footprint in the overall ecology of earth.

So far our time frame for sustainability extends no further than 100 years. Oil and natural gas companies issued promotional materials in recent years touting a U. S. natural gas supply "for the next 100 years." No one suggests that another supply will be found for the 100 years after this supply is used up. And this illustrates our dilemma.

When discussing non-renewable resources such as coal, oil and natural gas or when discussing the unsustainable use of renewable resources such as fresh water, trees, fish or a multitude of other things, we need to explicitly calculate and state how long each resource will last at the present rate of use. If, for example, natural gas (a non-renewable resource) will be used up in 100 years at the present rate of use and oil reserves will be used up in 50 years, then this says something

about the projected length of our industrial civilization. Coal has greater reserves and a longer potential period before it can be used up, but it cannot take the place of oil and natural gas.

And these calculations don't even address the issue of CO₂ concentration in the atmosphere from mining and burning all this coal, oil and natural gas and the effects of the resulting climate change on earth ecology and human civilization or the time frame of these effects.

We are but one species of life on earth. Getting a rational grasp on our sustainable outlook requires that we look behind us and consider the whole stream of life.

Life on earth, in its simplest form, began about 4 billion (4×10^9) years ago, about a half-billion years after the earth formed. For about $3 \frac{1}{2}$ billion years there were only single-celled life forms on earth. Multi-cellular life forms began to develop during the Cambrian period, about 500 million years ago, leading to an expansion of plants and animals in the seas. Life on earth faced good times and bad over the following 500 million year period, impacted by continental drift, poison gases from volcanoes, growing and declining greenhouse gases, the huge increase in oxygen content in the earth atmosphere as well as meteor impacts. Species died, ice ages came and went, evolution created new species and sometimes massive extinctions revised the landscape of life on the planet.

Precursors to humans showed up about 7 million years ago. Recognizable homo-sapiens arose about 125,000 years ago. Hunter-gatherer tools and practices slowly advanced. About 18,000 years ago the last ice age began to retreat and climates began to warm. This began the mild climate period in which we are still living today. Agricultural societies began to develop about 10,000 years ago. About 5,000 years ago writing was developed, beginning the initially sparse historical written record of humanity.

European science began to emerge about 500 years ago. And the industrial era began about 250 years ago. A general appreciation of humanity's adverse impact on the earth's ecology emerged about 40 years ago. And our collective will to address these adverse impacts, other than conversationally, may not have begun yet.

In comparison to the enormous time frame of life's history on earth, we humans aren't even a speck on life's page. Yet our lives are important to us. That is why we need to ask ourselves: How long will our species last? The earth, as can be seen from the long journey of life, doesn't care whether humans are present or not. So we have to care.

If the human population continues to grow and we continue to overuse renewable resources and rapidly use up non-renewable resources over the next 100 years, then

industrial/technological civilization, given our current scientific and technological knowledge, will collapse. We need to ask if this is an acceptable outcome.

If we want to ensure an industrial/technological future for more than 100 years, we need to spell out the conditions for achieving this goal. We could pool international knowledge and develop best estimates for sustainable yields of renewable resources and equal access to non-renewable resources for whatever future period we can agree upon for planning purposes. And we could devote ourselves to keeping these estimates current each year or every few years, whatever is practical and agreeable.

This data in hand we could then intelligently discuss the human future and calculate use rates for each renewable and non-renewable resource we make use of. And, having come this far, we can discuss equity across both space and time—equity for those living today and equity for those living for whatever defined future we can agree upon.

As difficult as it is to envision equitable distribution of resource use among the people living today, it is even more difficult to envision equitable distribution of resource use among the present and future generations of humanity. This is largely unexplored territory. There is a lot of talk about concern for future generations but this concern is kept

comfortably vague. We have to be very specific. The only way that generational equity, of whatever length we agree upon, is possible is to take the best estimate of each non-renewable resource and divide that number by the number of years we agree upon for planning purposes. What is the right number of years? One hundred seems inadequate. Five hundred years seems like a minimal time horizon.

What are the implications of a 500 year time horizon? Using oil as an example, the world currently uses about 35 billion barrels of oil per year. The estimated reserves are about 1,678 billion barrels, a 48 year supply at the current rate of use. If we adopted a 500 year time horizon, we would divide 1,678 billion barrels by 500 years and get an annual allocation of 3.4 billion barrels. This would require a 90% reduction in our current rate of use. Even if this reduction were phased in over 10 years, this would require almost 7% per year reduction in the use rate until the goal is met.

Given the demonstrated nature of human beings and our individual and collective decision-making processes, probably no reduction in use rates of non-renewable resources is possible and certainly not unless it is accompanied by equity among the living. So that is it: no equity among the living and no equity with future generations. Perhaps 80%-90% of our technologies rest on a sea of oil. In about 50 years the oil era

will come to an end and along with it our current advanced civilization. Either unexpected gigantic new oil discoveries or dramatic new recovery processes will be required to keep it going a bit longer. Or we must make unexpected and astonishing new scientific discoveries that substitute some other resource for oil.

The only thing certain is that the earth will go on. When the human species will come to an end is unknown. But once technological civilization comes to an end, the influence of humans will recede as geological and evolutionary forces return to the forefront. Perhaps humanity will continue but with a much smaller ecological footprint and a much-reduced population.

One hopes that the human species can do better than this, but we may have built-in limitations of mind and emotions that preclude the full use of our reason for cooperation in the interest of all of us and to maintain the beautiful world we live in.